Special Topics on Basic EECS I
VLSI Devices
Lecture 24

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Drain current

- Using the previous approximation,
  - We can obtain the following expression:

$$I_d = \mu_{eff} \frac{W}{L} \left\{ C_{ox} \left(V_{gs} - V_{fb} + \frac{k_B T}{q} \right) \phi_s - \frac{1}{2} C_{ox} \phi_s^2 - \frac{2}{3} \sqrt{2\epsilon_{si} q N_a} \phi_s^{1.5} + \frac{k_B T}{q} \sqrt{2\epsilon_{si} q N_a \phi_s} \right\} \Bigg|_{\phi_{s,s}}^{\phi_{s,d}}$$

Taur, Eq. (3.21)

  - Only with $\phi_{s,s}$ and $\phi_{s,d}$, we can evaluate the drain current.

Let's evaluate it together! (1)

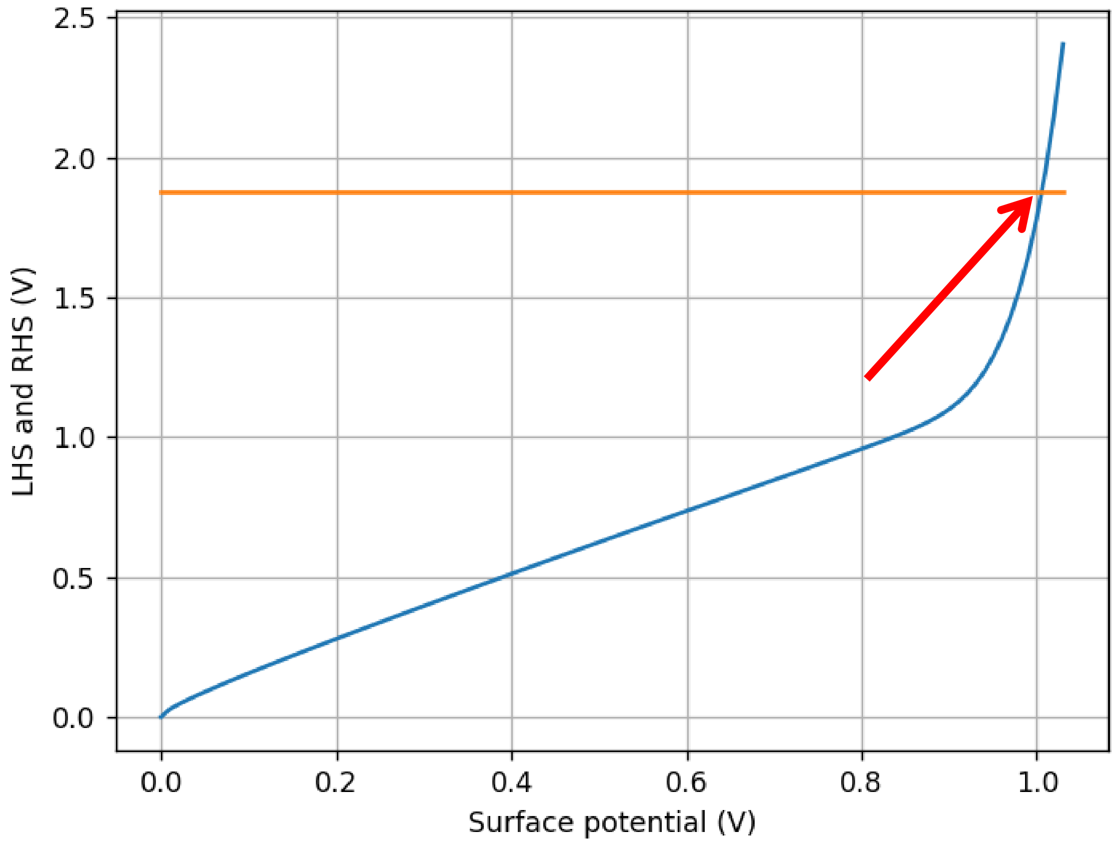
- Step-by-step
  - Assume that N_a = 10^{17} cm^{-3}, t_{ox} = 10 nm, V_{gs} = 1.0 V, and V_{fb} = -0.88 V.
  - Consider a case of V_{ds} = 0.1 V.
  - First, we must calculate $\phi_{s,s}$. How?

$$1.88 = \phi_{s,s} + \frac{\sqrt{2\epsilon_{si} k_B T N_a}}{C_{ox}} \left[\frac{q\phi_{s,s}}{k_B T} + \frac{n_i^2}{N_a^2} \exp\left(\frac{q}{k_B T} \phi_{s,s} \right) \right]^{1/2}$$

Let's evaluate it together! (2)

- Graphical solution
  - Draw the LHS and RHS.

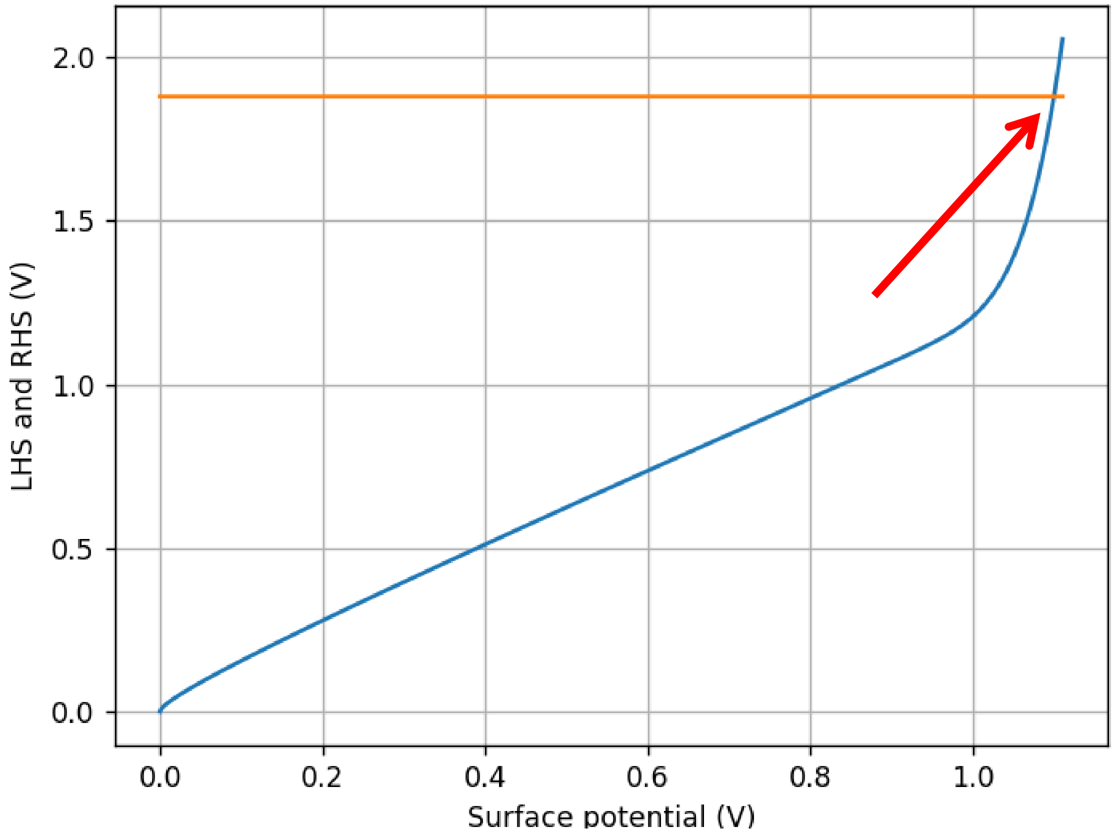
  $\phi_{s,s}$ = 1.006 V



Let's evaluate it together! (3)

- Now, for the drain end.
  - We must calculate $\phi_{s,d}$.

$\phi_{s,d}$ = 1.100 V



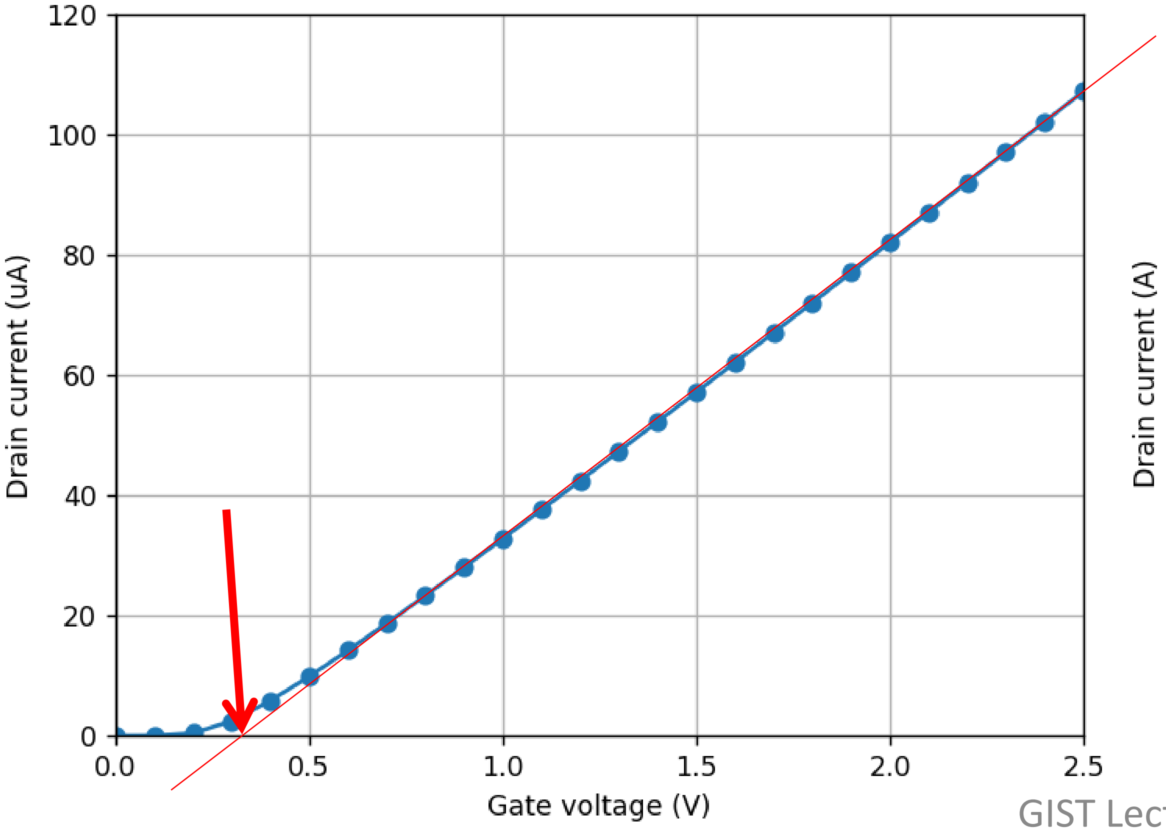
$$1.88 = \phi_{s,d} + \frac{\sqrt{2\epsilon_{si} k_B T N_a}}{C_{ox}} \left[\frac{q\phi_{s,d}}{k_B T} + \frac{n_i^2}{N_a^2} \exp\left(\frac{q}{k_B T} (\phi_{s,d} - 0.1) \right) \right]^{1/2}$$

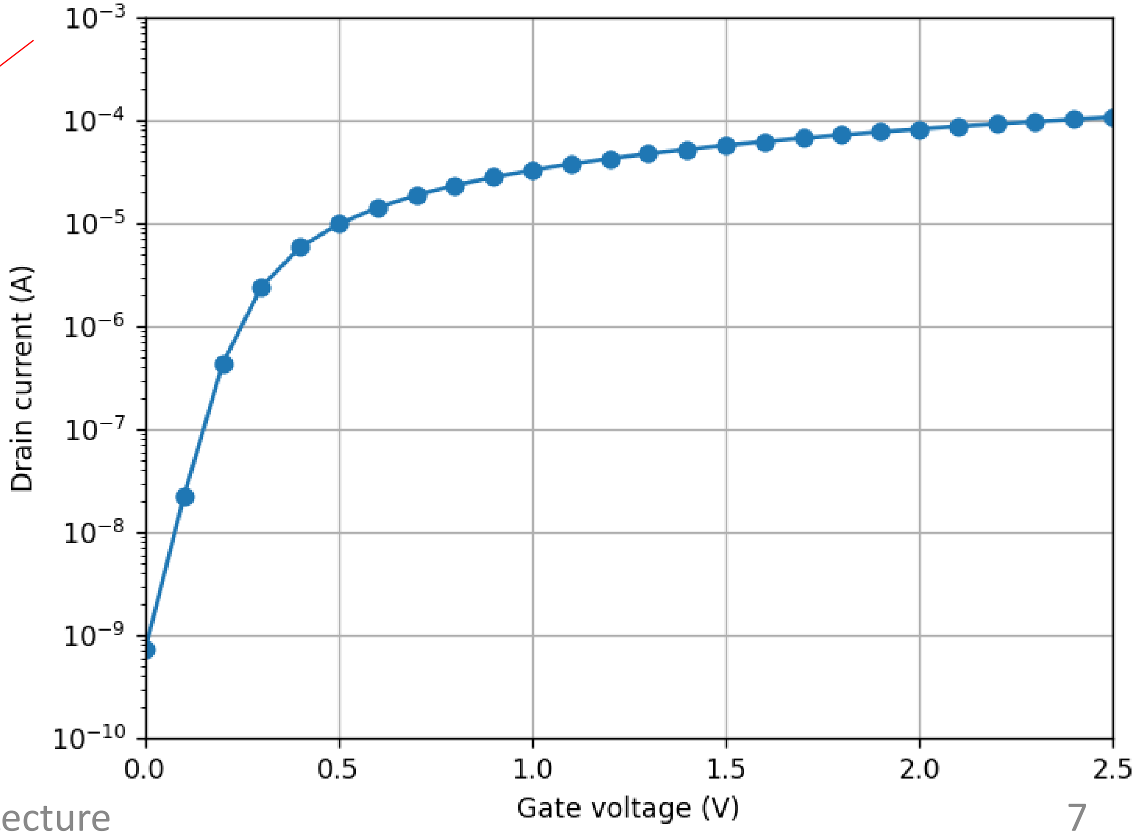
Let's evaluate it together! (4)

- Now, we can calculate I_d.
  - Evaluate $C_{ox}\left(V_{gs} - V_{fb} + \frac{k_B T}{q}\right)\phi_s - \frac{1}{2}C_{ox}\phi_s^2 - \frac{2}{3}\sqrt{2\epsilon_{si} q N_a}\phi_s^{1.5} + \frac{k_B T}{q}\sqrt{2\epsilon_{si} q N_a \phi_s}$ twice with $\phi_{s,s}$ = 1.006 V and $\phi_{s,d}$ = 1.100 V.
  - Values are $1.3442\text{X}10^{-6}$ C V cm^{-2} and $1.4096\text{X}10^{-6}$ C V cm^{-2}.
  - When $\mu_{eff}\frac{W}{L}$ is 500 cm^2 V^{-1} sec^{-1}, I_d is about 32.76 μA.

Input characteristics (at a low V_{ds}, 0.1 V)

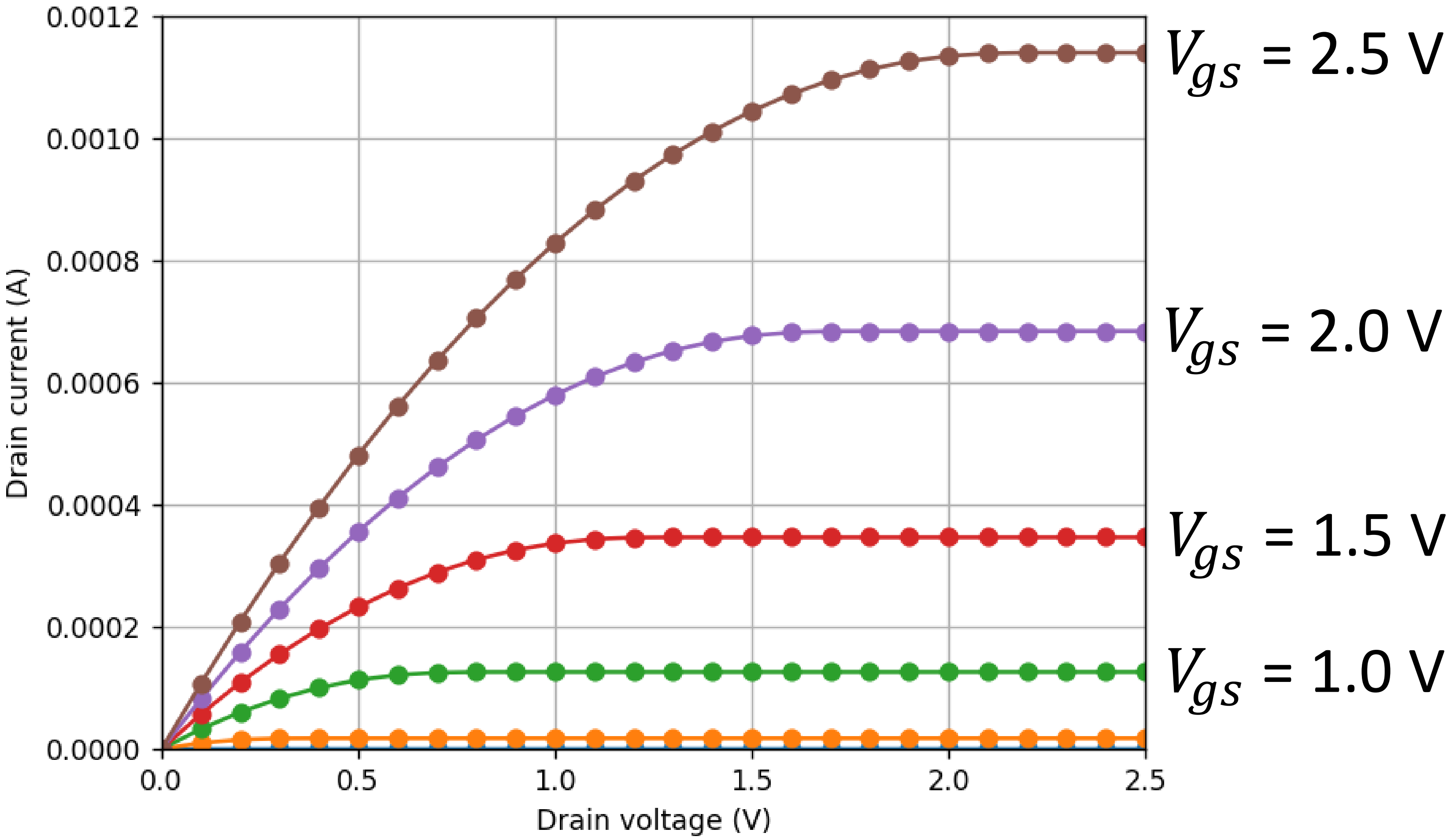
- Increase V_{gs} up to 2.5 V.
  - Linear scale and semi-log scale





Output characteristics

- Increase V_{ds} up to 2.5 V at various V_{gs} values.



Regional approximations

- After the onset of inversion but before saturation,
  - The surface potential, $\phi_s(y)$, can be approximated by

$$\phi(0, y) = V(y) + 2\phi_B$$

Taur, Eq. (3.3)

  - It means that

$$\phi_{s,s} = 2\phi_B$$
$$\phi_{s,d} = 2\phi_B + V_{ds}$$

  - In this case, $\frac{dV}{d\phi_s} = 1$. We must calculate the following term for $\phi_{s,d}$:

$$C_{ox}(V_{gs} - V_{fb})(2\phi_B + V_{ds}) - \frac{1}{2}C_{ox}(2\phi_B + V_{ds})^2 - \frac{2}{3}\sqrt{2\epsilon_{si}qN_a}(2\phi_B + V_{ds})^{1.5}$$

A simpler form of I_d

- By taking the difference, we can find a simpler form:

$$I_d = \mu_{eff}\frac{W}{L}\left\{C_{ox}\left(V_{gs} - V_{fb} - 2\phi_B - \frac{1}{2}V_{ds}\right)V_{ds} - \frac{2}{3}\sqrt{2\epsilon_{si}qN_a}\left[(2\phi_B + V_{ds})^{1.5} - (2\phi_B)^{1.5}\right]\right\}$$

Taur, Eq. (3.22)

  - For a given V_{gs}, I_d first increases linearly with V_{ds}, then gradually levels off to a saturated value.

Linear (triode) region

- When V_{ds} is small, we may keep only up to the first order.

$$I_d = \mu_{eff}\frac{W}{L}\left\{C_{ox}\left(V_{gs}-V_{fb}-2\phi_B\right)V_{ds}-\frac{2}{3}\sqrt{2\epsilon_{si}qN_a}\left[\frac{3}{2}(2\phi_B)^{0.5}V_{ds}\right]\right\}$$

$$= \mu_{eff}\frac{W}{L}C_{ox}\left(V_{gs}-V_{fb}-2\phi_B-\frac{\sqrt{4\epsilon_{si}qN_a\phi_B}}{C_{ox}}\right)V_{ds}$$

$$= \mu_{eff}\frac{W}{L}C_{ox}\left(V_{gs}-V_t\right)V_{ds}$$

Taur, Eq. (3.23)

  - The threshold voltage, V_t, is given by

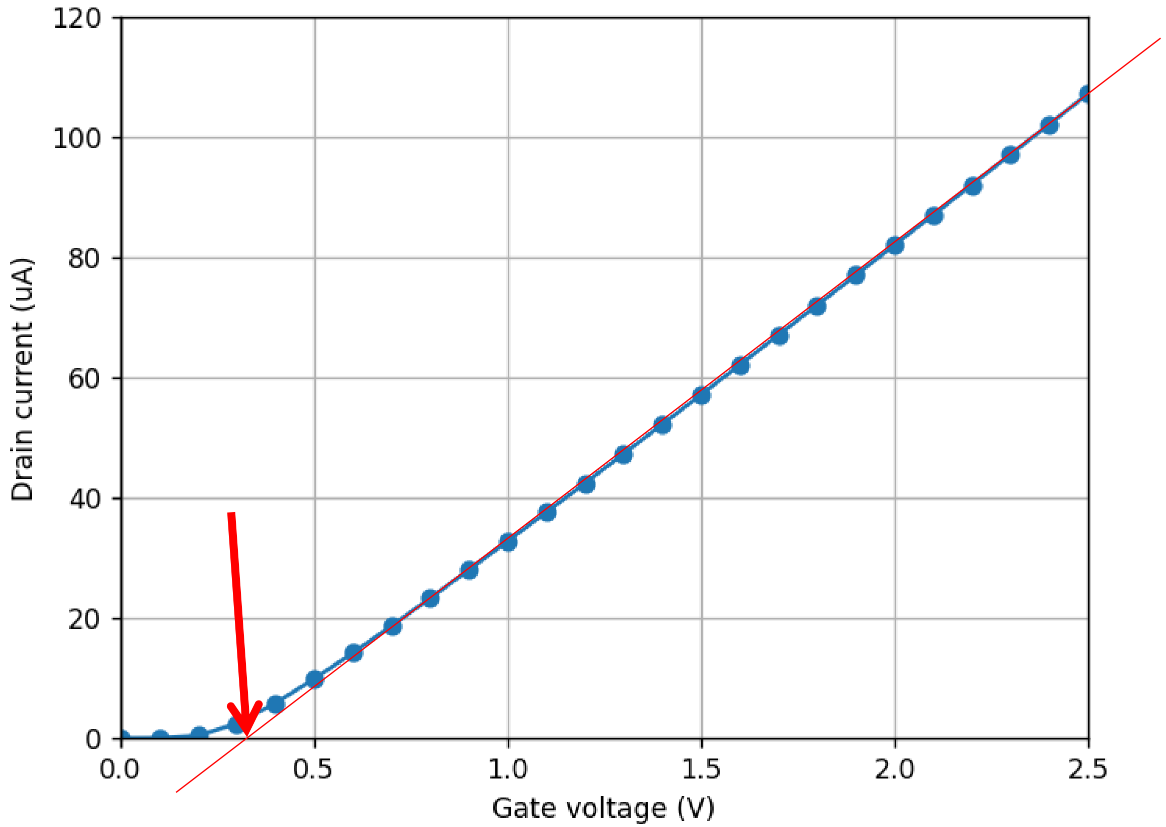
$$V_t = V_{fb} + 2\phi_B + \frac{\sqrt{4\epsilon_{si}qN_a\phi_B}}{C_{ox}}$$

Taur, Eq. (3.24)

  - It is the gate voltage when the surface potential reaches at $2\phi_B$.

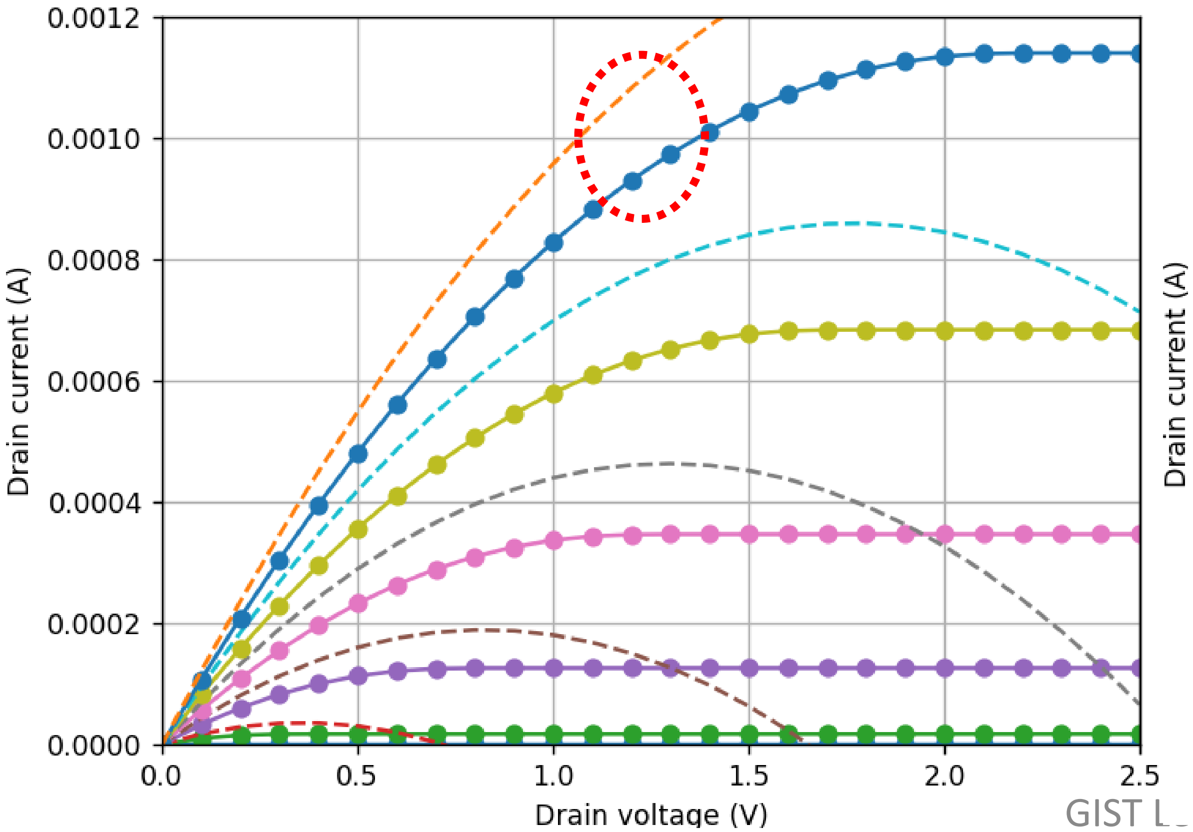
In our previous example,

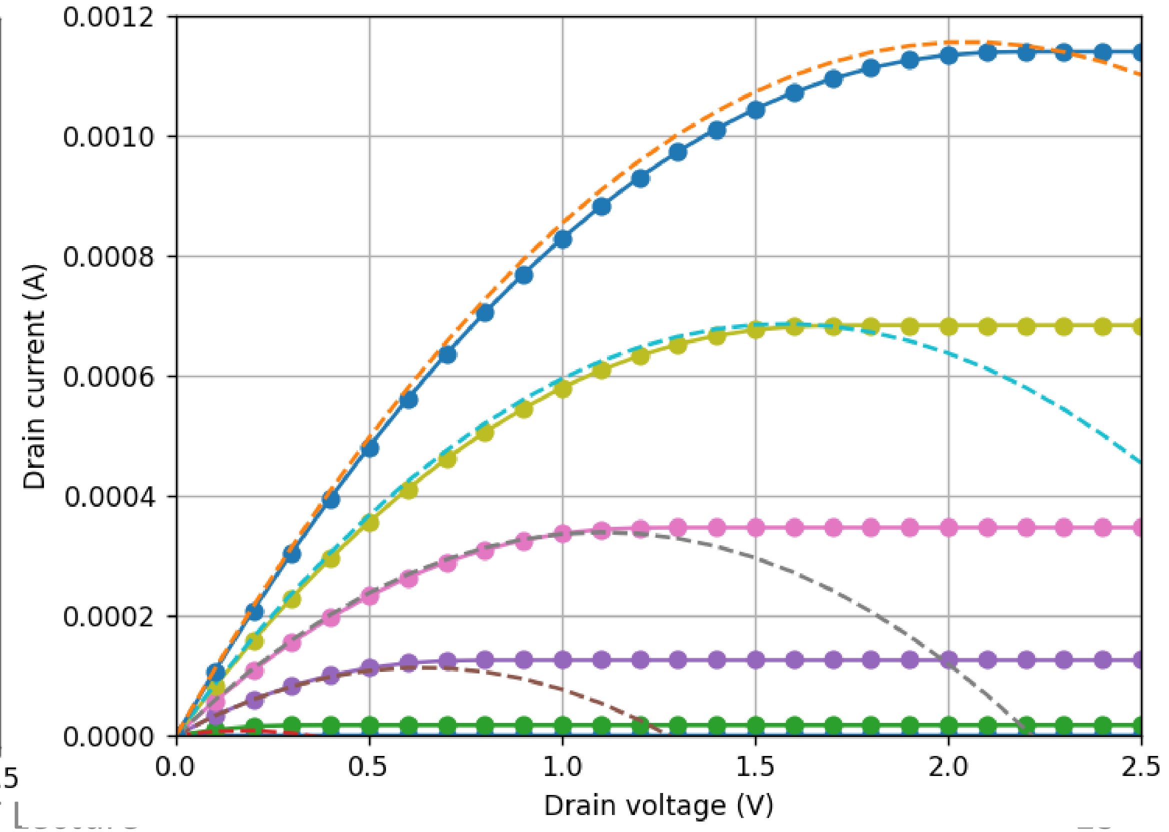
- The threshold voltage is about 0.11 V.
  - In reality, a *linearly extrapolated threshold voltage* is slightly higher than the "$2\phi_B$" V_t.



Comparison

- Output characteristics by Taur, Eq. (3.22) & Taur, Eq. (3.23)
  - Difference in V_t (~0.2 V)





Parabolic region

- We must keep up to the second order.

$$I_d = \mu_{eff}\frac{W}{L}\left\{C_{ox}\left(V_{gs} - V_{fb} - 2\phi_B - \frac{1}{2}V_{ds}\right)V_{ds} - \frac{2}{3}\sqrt{2\epsilon_{si}qN_a}\left[\frac{3}{2}(2\phi_B)^{0.5}V_{ds} + \frac{3}{8}(2\phi_B)^{-0.5}V_{ds}^2\right]\right\}$$

$$= \mu_{eff}\frac{W}{L}\left\{C_{ox}\left(V_{gs} - V_t - \frac{1}{2}V_{ds}\right)V_{ds} - \frac{1}{4}\sqrt{2\epsilon_{si}qN_a}\left[(2\phi_B)^{-0.5}V_{ds}^2\right]\right\}$$

$$= \mu_{eff}\frac{W}{L}\left\{C_{ox}(V_{gs} - V_t)V_{ds} - \frac{1}{2}C_{ox}\left[1 + \frac{\sqrt{\epsilon_{si}qN_a/(4\phi_B)}}{C_{ox}}\right]V_{ds}^2\right\}$$

Taur, Eq. (3.25)

Let's introduce a factor, m.

- It is given as

$$m = 1 + \frac{\sqrt{\epsilon_{si} q N_a / (4\phi_B)}}{C_{ox}}$$ Taur, Eq. (3.26)

  - From the maximum depletion width,

$$W_{dm} = \sqrt{\frac{4\epsilon_{si}\phi_B}{qN_a}}$$ Taur, Eq. (2.190)

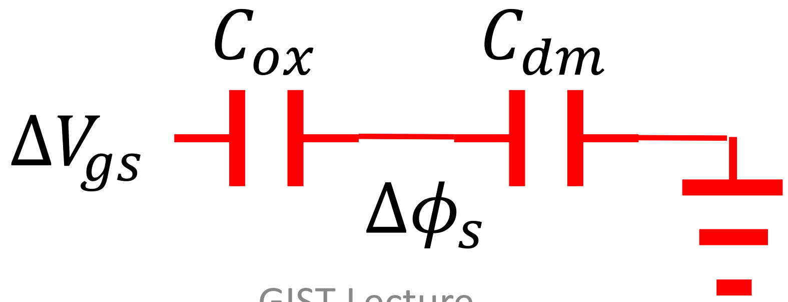
  - An alternative form is available,

$$m = 1 + \frac{C_{dm}}{C_{ox}} = 1 + \frac{3t_{ox}}{W_{dm}}$$ Taur, Eq. (3.27)

  - In our previous example? It was about 1.1. (Due to a low N_a)

Its physical meaning

- Serial capacitors give $\frac{C_{ox}C_{dm}}{C_{ox}+C_{dm}}$.
  - Charge across the oxide capacitor:
$$\frac{C_{ox}C_{dm}}{C_{ox}+C_{dm}}\Delta V_{gs} = C_{dm}\Delta\phi_s$$
  - Therefore,
$$m = \frac{C_{ox}+C_{dm}}{C_{ox}} = \frac{\Delta V_{gs}}{\Delta\phi_s}$$
  - m should be kept close to one.



Saturation current

- Maximum value of I_d at a given V_{gs}
  - Recall that

$$I_d = \mu_{eff}\frac{W}{L}\left\{C_{ox}\left(V_{gs}-V_t\right)V_{ds}-\frac{m}{2}C_{ox}V_{ds}^2\right\} \quad \text{Taur, Eq. (3.25)}$$

  - When $V_{ds}=V_{dsat}=\frac{V_{gs}-V_t}{m}$,

$$I_d = I_{dsat} = \mu_{eff}C_{ox}\frac{W}{L}\frac{\left(V_{gs}-V_t\right)^2}{2m} \quad \text{Taur, Eq. (3.28)}$$

Thank you!